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Review of visualising LCA results in the design process of buildings

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ABSTRACT

Life Cycle Assessment (LCA) is increasingly used for decision-making in the design process of buildings and neighbourhoods. Therefore, visualisation of LCA results to support interpretation and decision-making becomes more important. The number of building LCA tools and the published literature has increased substantially in recent years. Most of them include some type of visualisation. However, there are currently no clear guidelines and no harmonised way of presenting LCA results. In this paper, we review the current state of the art in visualising LCA results to provide a structured overview. Furthermore, we discuss recent and potential future developments. The review results show a great variety in visualisation options. By matching them with common LCA goals we provide a structured basis for future developments. Case studies combining different kinds of visualisations within the design environment, interactive dashboards, and immersive technologies, such as virtual reality, show a big potential for facilitating the interpretation of LCA results and collaborative design processes. The overview and recommendations presented in this paper provide a basis for future development of intuitive and design-integrated visualisation of LCA results to support decision-making.

1. Introduction

1.1. Life cycle assessment of buildings

Life Cycle Assessment (LCA) is increasingly used for the assessment of the environmental performance of buildings [1,2]. Different countries use LCA results as part of their building regulations. It has become mandatory to submit a calculation of the so-called embodied environmental impact related to the manufacturing of building materials as part of the building permit application process in the Netherlands [3], for example. Sweden will introduce a mandatory calculation of the embodied greenhouse gas (GHG) emissions for new residential buildings in 2021 [4]. Furthermore, LCA has become a relevant part of several green building certification systems (GBCS), such as BREEAM [5] or the system by the German Sustainable Building Council (DGNB) [6], amongst others.

LCA is still often considered as a complicated method for experts [7,8]. The method has been developed initially for consumer products and is standardised in the ISO 14040/44 [9,10] framework. The method consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. EN 15804 [11] has been developed for the LCA of building materials and provides a basis for Environmental Product Declarations (EPDs). EN 15978 [12] describes one approach for the LCA of a building and defines several life cycle stages: A production and construction, B use, and C end-of-life of buildings. A separate stage D describes the benefits and loads beyond the system boundaries, for example in the case of recycling. To simplify the process and decrease the amount of work, most building LCA studies use predefined datasets for the materials or components. Databases especially developed for building materials, such as KBOB [13] or ökobau.

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dat [14] provide the data. Furthermore, more and more building material manufacturers publish EPDs of their products.

By using the predefined data, the LCI and LCIA are merged into one step and simplified [15]. Many aspects of the goal and scope, such as functional unit or reference study period are defined in the national standards or the guidelines for GBCS. Furthermore, it is defined which environmental indicators should be provided as results, e.g. Sweden will only make Global Warming Potential (GWP) mandatory, while Switzerland looks at GWP, the Primary Energy Non-Renewable Total (PENRT) and a single-score indicator called *Umweltbelastungspunkte* (UBP). This indicator is specifically calculated for Switzerland based on the method of ecological scarcity [16]. The DGNB system uses five environmental output indicators, and PENRT and the Primary Energy Renewable Total (PERT) in addition.

1.2. Need for visualisation

However, the form in which the LCA results should be communicated is not clearly defined. The EeBGuide [17] includes guidelines and templates for reporting of the results, but they aim at LCA experts. Furthermore, the European Joint Research Centre published a guideline for the interpretation of results for LCA experts [18].The American Institute of Architects issued an extensive guide for building LCA, but only mention a benchmark comparison as support for interpretation [19]. There are no guidelines for interpretation of LCA results addressing a wider range of stakeholders involved in the building design.

As a result, the interpretation phase of LCA is still considered complex [20,21]. Previous studies in this field [22,23] provide evidence that one of the obstacles to the broader use of LCA is the difficulties in the understanding and communication of results. Often the LCA results are not comprehensible for stakeholders such as policy and decision makers, although previous research demonstrates that the integration of life cycle aspects in the design process can improve decision-making involving non-experts [24]. In current practice, LCA results of buildings are used for certification and documentation, but barely to improve the building design or fundamental decisions related to the intended project [25,26]. To use LCA results as basis for decision-making in the design process, the results have to be interpretable. At the same time, the interaction and cooperation between the different stakeholders and the exchange of relevant data and information between them should be promoted [24].

Here, a particular emphasis on suitable visualisations can provide the necessary information and decision support. The importance of visualisation of LCA results has been widely discussed in the literature [23,27,28]. Visualisation techniques are usually used to communicate and analyse data and information. For example, they can make information easy to explore and more useable when the volume of information grows [29]. The field of visualisation is closely related to the visual analytic field, which intends to reduce complex cognitive work and is "required to process large data sets towards enabling an informed decision-making" [23]. The application of visualisation techniques has been expanded to different disciplines and domains, especially to those that involve an extensive use of data, such as LCA. Hence, regarding the potential of the visual analytics to improve the understanding of LCA results, visualisation can facilitate efficient human cognitive capabilities by amplifying cognitive sensors, reducing search/lost, enhancing the pattern recognition and supporting easy reasoning, among others [30]. Considering the different application areas of LCA (e.g. EPDs, design optimisation, or legislative decisions taken by policy makers), each application focuses on different stakeholders, and each one has its information requirement [23]. As such, visualisation is key for decision support [28], but also optimisation of the design during the design process [31].

In 1996, Shneiderman defined a type by task taxonomy based on the common visual information seeking mantra "overview, zoom and filter, details on demand" [29]. If provide at the right time and in the right form, visualisations can support the information seeking. If designers cannot intuitively match the results with the architectural design then there is a tendency that the analyses performed will not affect the actual design decisions [32]. In contrast, if the visualisations are meaningful to designers, significant improvement of the environmental impact can be achieved [33] and collaboration in interdisciplinary design teams is improved [34].

While the need for visualisation is evident and often stated in the literature, few researchers have focussed on developing visualisations for building LCA results. These few studies [33,35–38] propose novel types of visualisation often dedicated to one type of stakeholder involved in the design process of a building. These studies compare a few visualisation types, but a comprehensive review of visualisation of building LCA results is currently not available. Although the number of building LCA tools has been growing recently, they provide limited visualisation options. Currently, there is no harmonisation between the ways of visualising building-related LCA results neither in practice nor in academia. This makes it especially difficult for practitioners and non-LCA expert to make use of the LCA results.

1.3. Goal

The paper aims to review the current state of the art in visualising LCA results for buildings. We will collect the visualisations used in current building LCA software tools and the scientific literature and cluster the different approaches to provide an overview. This overview should provide a starting point for improved visualisation of LCA results and harmonisation. Furthermore, we discuss the potential using the visualisation of LCA results in design interfaces that support decision-making in the design phase of buildings.

2. Method

The method consists of three parts. In the first part, we define typical goals for conducting LCA in the design process. In the second part, we collect and analyse visualisation options from both building LCA software tools and the scientific literature in the field. The building LCA tools are used to cover the state of the art in practice while the literature is analysed to review the current research. In the third part, we define categories to classify the different visualisation options found in the review.

2.1. Definition of goals during the interpretation phase of LCA

We define six typical goals during the interpretation phase of LCA results where visualisations are used.

1. Identification of hotspots
   Many LCA studies are conducted to identify so-called hotspots that are responsible for a large share of the environmental impact. This hotspot analysis can be conducted at different levels of detail. In the case of buildings, the aim is often to identify building elements (walls, roof, etc.), individual materials, or life cycle phases with a large environmental impact.
2. Comparison of options for design improvement
   If the aim is to use the LCA results to improve the design or decide between several design alternatives, a comparison becomes crucial. The comparison can be carried out on different levels of detail, for example comparing different buildings, different building elements or building materials.
3. Correlation, uncertainty, and sensitivity analysis
   The analysis of the correlation of parameters or indicators becomes important when the aim is to optimise a design towards different criteria, see for example [39]. The correlation analysis is often applied to support design guidance to make appropriate choices based on a large set of options instead of only a few. Uncertainty

analysis often refers to the uncertainty inherent to the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty, and data variability [9]. Furthermore, sensitivity analysis is often carried out in the interpretation phase to test the influence of modelling choices, such as system boundaries, allocation approaches or the choice of specific datasets [40], on the overall assessment results.

4. Benchmarking

   Especially with regards to fulfilling thresholds defined in national building regulations or GBCS, benchmarking becomes very important. Additional benchmarks could include national averages, previous projects or the average within a building portfolio. Furthermore, global targets, such as the 2° target or global frameworks, such as the planetary boundaries [41] or 2000 Watt society [42] can be used as benchmarks.

5. Spatial distribution

   This aspect relates to the aim of identifying where environmental impacts are caused. Therefore, maps are often used to highlight the spatial distribution of the impact, e.g. [43].

6. Temporal distribution

   To identify when environmental impacts are caused, often charts plotting the development of the impact over time are used, e.g. over the lifetime of the building [44].

2.2. Analysis of existing visualisation options

The main research question for the review is "Which types of visualisation of LCA results are used when and for which stakeholders during the design process of buildings?" To answer this main research question, three sub-research questions are used for the review of both the building LCA software and the scientific literature. The options for the answers are explained in more detail in section 2.3.

1) Which design stage is targeted?
2) Which are the intended stakeholders?
3) Which visualisation types are used?

We reviewed the currently most commonly used LCA software tools for buildings. The list of tools is based on previous reviews [45,46]. We updated and extended the list based on input from the IEA EBC Annex 72 [47] researchers. The final list includes 39 LCA software tools dedicated explicitly to buildings or building components. The majority of tools have been developed for whole building LCA, but most of them also allow for the assessment of individual components. It cannot be guaranteed that all building LCA tools are included, but we are sure to have covered the most common ones based on the expert feedback. We therefore assume the analysed tools to be sufficient to provide an overview of the field. The information about the tools was collected based on free demo versions, experts' feedback using the tools and freely available online material such as tutorials, demo videos, and handbooks. Tools that were not published or where there was no information accessible were excluded from the review. Seven of these tools were excluded from the analysis due to lack of information leading to 32 analysed tools.

To identify different visualisation approaches presented in scientific literature, we conducted a systematic literature review, based on the protocol for Systematic Literature Review (SLR) and including additional studies via the 'snowball' approach [48,49]. As the aim is to identify studies addressing the visualisation of LCA aspects related to buildings and construction, we conducted the systematic search using the keyword string: "(LCA OR life cycle assessment OR life cycle analysis) AND (building OR construction) AND (visualization OR visualisation)". The search was performed via 'ScienceDirect', searching the selected terms in the papers' "abstract, title or author-specified keywords". Documents identified through the SLR protocol were screened based on their title and abstract and excluded if out of scope (e.g. if they were not addressing buildings or construction). The database search was conducted in April 2020. The addition of snowball studies continued until submission of the manuscript.

The SLR provided 32 papers. 16 papers were removed from the review as the main focus was not LCA of buildings. 23 papers were added following the snowball approach and using expert knowledge. Primarily, literature focusing on visualisation methods and development of new LCA methods or tools was added. Secondly, case studies were added that provide novel or unique types of visualisations. As there are a large number of building LCA case studies using at least one type of visualisation, it is impossible to include all. Therefore, the snowball approach was stopped when no new types of visualisations could be found. Finally, 39 papers were included. Although we selected literature on visualisation method or tool development first, most of the analysed papers present case studies. Eleven papers aim at providing visualisation methods or examples for building LCA. The majority of analysed papers are scientific journal papers followed by peer-reviewed papers in conference proceedings. One book was added as grey literature, because this type of visualisation could not be found in the peer-reviewed literature.

2.3. Definitions for classification

2.3.1. Definition of design stages

Design stages in the planning process of buildings are usually defined differently by different stakeholders and in different national contexts. Furthermore, no common definition is used in the analysed literature to further specify the intended design stages. Therefore, we only differentiate between an early and a detailed design phase and use the joint model proposed within IEA EBC Annex 72 [47], see Fig. 1. We define the early design phases as including the strategic definition, preliminary studies and the concept design phase, typically including sketches and the competition design (phases 0 to 2). Often there is a break in the tools and sometimes the design team after this phase. The detailed design phase describes the development of the design until the completion of the building, including the building permit application, tendering, construction drawings and the construction itself (phases 3 to 6). The operational and end-of-life phase are significant considering the life cycle but excluded here due to the limited influence of the stakeholders involved in the planning process on these phases.

2.3.2. Definition of stakeholder groups

Three groups of stakeholders, which can be expected to have an increasing level of expert knowledge regarding LCA are defined based on their role in the design process.

1) *Decision-makers* are defined as the group responsible for the final decision. Often these stakeholders are responsible for the budget of the building. The group includes private and public clients, individual building owners, but also investors, project developers, housing associations, portfolio managers, policymakers, etc. In the case of participatory design processes, citizens can also be included in this group.
2) *Building design professionals* is used as a term to summarise all building experts without specific LCA training. The group mainly consists of architects and engineers involved in the design process.
3) *LCA experts* are a group typically consisting of sustainability consultants, auditors for GBCS, and researchers.

2.3.3. Definition of visualisation types

The different types of visualisation found in the review are sorted and structured. Charts with similar names but referring to the same visualisation type such as radial chart and spider chart are combined. Table 1 provides an overview with icons of the 27 visualisation types used in the analysis. Each type, its advantages and disadvantages and examples for application from the literature are described in Table A1 in the Supplementary Information.

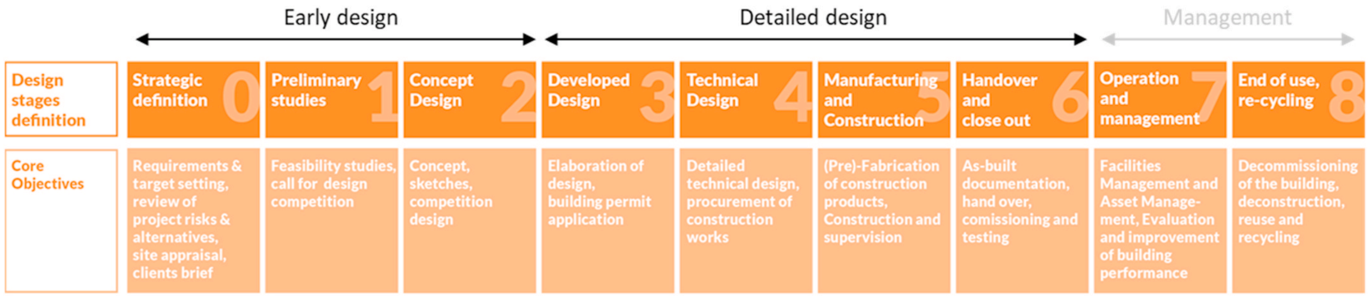


Fig. 1. Proposal for a joint model of building design and project phases within IEA EBC Annex 72 [47].

In the analysed literature, the general goal of the visualizations is to show the relation between design variables or design alternatives and the environmental impact. In most cases, there are multiple options to visualise the relation. Therefore, we introduce several categories. Four aspects are used to categorize the collection of visualizations specifically for the use in a building LCA study:

1. Number of environmental indicators.
   The representation of the environmental impact as a single-score value or multiple values is often discussed by LCA experts [83]. Therefore, the capability of visualising single or multiple indicators with different units in one graph (without aggregation) is used as one differentiation. If the aggregation into a global indicator is possible, it is seen as one indicator from the perspective of visualisation, because the values have the same unit and can be plotted on the same axis.
2. Type of variables.
   Visualised variables can be either discrete (e.g. construction material options or design alternatives) or continuous (e.g. fenestration ratio or insulation thickness), which is a key aspect in choosing the visualisation type. Each variable is plotted on a separate axis.
3. Number of variables.
   The number of evaluated variables can range from one (e.g. comparing a few fixed design alternatives will result in one categorical axis) to many (in a complex optimisation problem) and the possible number of visualised variables are limited by the dimensionality of the plot. Furthermore, it is important to mention that a colour scale or colour code can be seen as expressing another dimension of information. In general, the sum of indicators and variables gives the dimensionality of the graph.
4. Hierarchy levels.
   The hierarchic decomposition of the results plays a key role in finding hotspots. The hierarchy may refer to lifecycle stages, the decomposition of the object (e.g. building components) or even to environmental aspects in case of an aggregated indicator. Different visualisations can be used to express hierarchic data, but the level is limited by the type of visualisation. We differentiate between non-hierarchic charts, visualisations with one level of hierarchy (parent-child), and multiple (deep) levels of hierarchy.

Using these aspects for categorisation, eight groups of visualisation types are identified within the collected visualizations. The categorisation process is shown in Fig. 2.

3. Results

3.1. General analysis of building LCA tools and the literature

The full table of the review of the building LCA tools and the scientific literature can be found in Tables A2 and A3 in the Supplementary Information.

The analysis showed that most building LCA tools focus on the detailed design stages (see Fig. 3) while there are slightly more scientific papers addressing the early design stages. Most tools address several design stages but have a focus either on the early or detailed design stages. If this differentiation was not provided by the tool developers, expert judgement was used for classification.

The results furthermore show that most building LCA tools intend to address building design professionals. No tool tries to specifically address decision-makers. As most tools claim to address several stakeholders, expert judgement was used to classify the tools to simplify the classification and provide clear results. Similar to the building LCA tools, the majority of the visualisations presented in the literature address building design professionals. About one third focusses on LCA experts, while only 12% address decision-makers.

3.2. Types of visualisations used

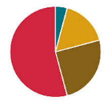
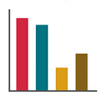
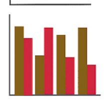
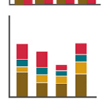
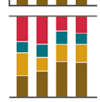
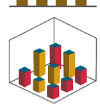
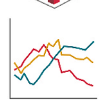
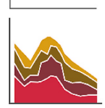
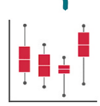
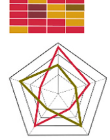
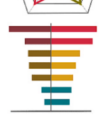
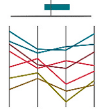
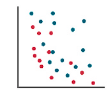
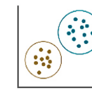
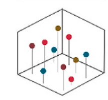
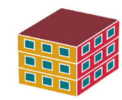
Counting the number of visualisations used by the building LCA tools reveals that most tools use more than one, but only a few types of visualisation, e.g. pie chart and bar chart. Only one of the analysed tools does not provide any visualisation. On average, three types of visualisations are used per tool, while the tool with most different types of visualisations uses eight types.

Bar charts and variations of it such as grouped or stacked bar charts are the clear majority, followed by pie charts (see Fig. 4). Those kinds are used by more than ten tools and can therefore be seen as common visualisations. Furthermore, the use of ‘complex’ visualisations with a large amount of information, such as scatter plots or parallel coordinate plots is very limited. The only tools that make use of a 3D colour code visualisation are developed by researchers. Currently, no commercial tool uses this kind of visualisation.

Like the building LCA tools, most published literature use bar charts and variations of it. A major difference to the results of the tools is the increased use of complex visualisations. Scatterplots sometimes including a Pareto front are used 12 times. Six publications use a representation on a 3D model. Five of them represent the colour code within the 3D design environment, while one uses Virtual Reality (VR) to show the results on the 3D model.

Analysing the hotspots regarding the use of visualisation options by building LCA tools for different stakeholders (see Table 2) shows that common visualisations (e.g. bar charts) are used as well as more complex visualisation options (e.g. scatter plots) for both LCA experts and building design professionals. For decisions-makers, we find that a small variety of visualisations is presented. The literature with a focus on visualisation provides more variety including options such as clusters or maps. The literature presenting case studies have a clear majority of common visualisations such as bar charts and variations of it. Scatter plots and Pareto fronts seem to be the only complex visualisations that are used by all types of papers. Although many authors in the analysed literature specifically focus on early design stages, no clear differences of the use of visualisations can be seen with regards to the design stages.

Table 1
Visualisation types found in the review.

#	Name and references with examples	Icon
1	Pie chart/donut chart [50,51]	
2	Multi-level Pie Chart [38,52]	
3	Sunburst [39]	
4	Vertical bar chart [33,39,43,52–59]	
5	Horizontal bar chart [39,52,58,60]	
6	Grouped bar chart [39,44,50,53,54,60–65]	
7	Stacked bar chart [39,44,54,57,59,60,64,66–69]	
8	Normalised bar chart [44,67]	
9	Multiple series 3D bar charts [61]	
10	Line chart [44,60,64,65,67,69,70]	
11	Stacked area chart [65]	
12	Sankey/Alluvial Diagram [71,72]	
13	Box plot [33,35,52,67,69,70,73,74,95]	
14	Tree map [65]	
15	Heat map [23,44,54,65,67]	
16	Radial chart/spider chart/polar chart [56,63]	
17	Tornado chart [33,75]	
18	Parallel coordinates [39,72,76,77]	
19	Pictorial unit chart [54]	
20	Pictorial fraction chart [66]	
21	Scatter plot [33,39,52,59,60,64,65,69,70,75,78,79]	
22	Cluster [27,69]	
23	3D Scatter plot [71,79]	
24	3D Colour code [35,36,38,43,74,80]	
25	Bubble map [43]	
26	Colour map [81]	
27	Scale [82]	

3.3. Synthesis of visualisation types and LCA goals

The results of the analysis of visualisation types are synthesised based on the goal of the interpretation phase and the category of visualisation type in Fig. 5. Several visualisation options exist for all the LCA goals. Therefore, they are ordered from left to right with the increasing amount of information transferred in the visualisation. In addition, the number of objects for the assessment proved to be relevant. From the visualisation aspect, each design alternative corresponds to a data point. One data point may consists of the hierarchically structured results, but the different data points cannot be aggregated. Therefore, a differentiation between one, few and many (>100) objects of assessments is introduced and indicated by the type of border around the icons in Fig. 5.

For the LCA goals of temporal distribution, spatial distribution, and benchmarking only two or three options each could be found in the literature. All these options are only suited to communicate one environmental indicator and one design variable. In the case of bar charts with a benchmark threshold, it is possible to show several environmental indicators next to each other, but this requires either normalisation or adding an individual axis for each bar, which would correspond to showing several single bar charts next to each other. The visualisation options that are part of group A and E have no hierarchy levels, while the stacked ordered area chart as part of group F has one hierarchy level that could be used to plot the evolution of the environmental impact of individual building elements and the sum for the whole building over time, for example.

Identification of hot spots and comparison of design options are the most common LCA goals in the reviewed literature and they show the highest variety of visualisation options. For identification of hot spots, only discrete variables are used. The options in group A, B, and C, all visualise one variable with increasing hierarchy levels, for example the embodied impact of building elements. The options in group D allow to visualise two variables, for example heating systems and insulation

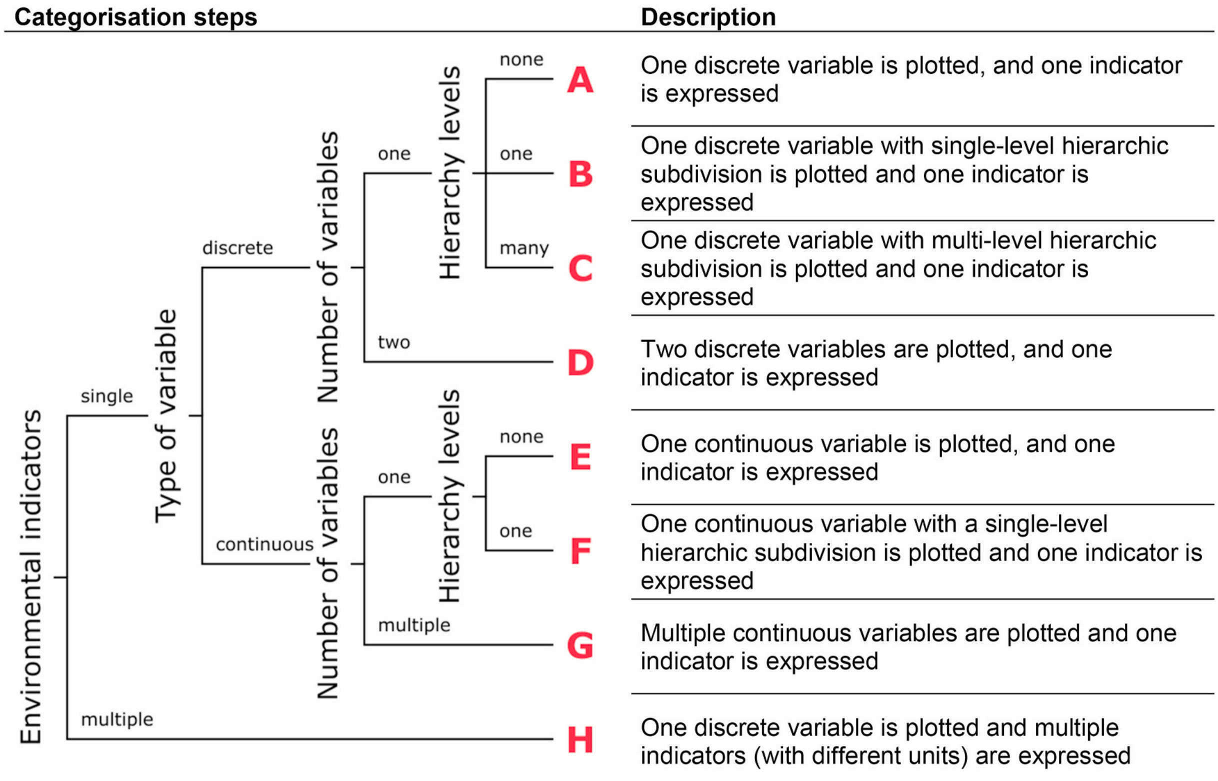


Fig. 2. Categorisation steps to define groups of visualisation types and description of the groups.

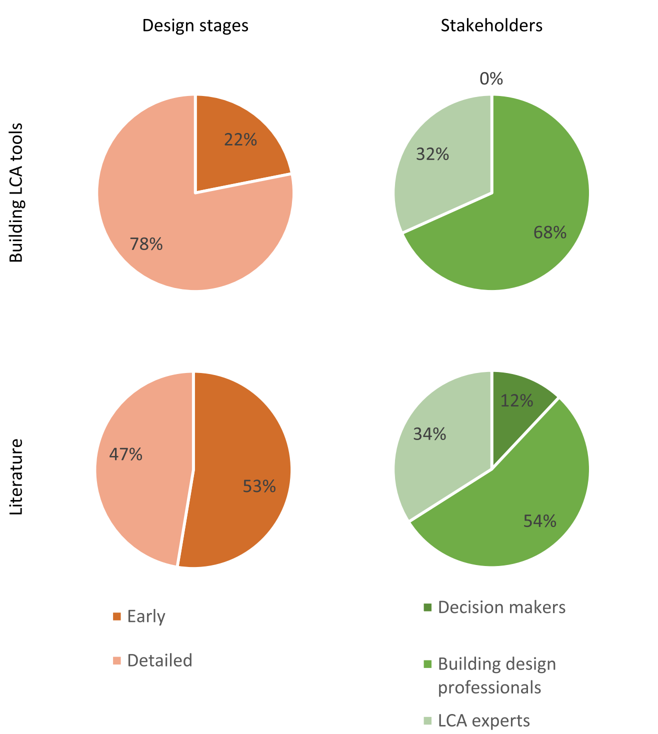


Fig. 3. Design stages and stakeholders mainly addressed by building LCA tools and the literature.

materials for renovation [62].

The comparison of design options can be visualised with a limited amount of information, such as a bar chart. If the number of options for comparison reaches a certain point, the type of visualisation becomes limited. Then mostly scatter plots are used to identify clusters or a Pareto front (group G). There is a lower limit for the number of objects for these types of charts to become meaningful. Parallel coordinate plots are often used to visualise several parameters and their interdependencies. If few design options are compared regarding multiple indicators, visualisation options of group H, such as spider charts, are used.

Uncertainty analysis is often an important part of LCA. A common way to visualise uncertainty is an error bar in bar chart or a box plot providing additional information by showing quantiles. A simple but rarely used approach in the analysed literature, is to show and rank the sensitivity of design parameter using a tornado chart [33]. The most common way to show correlation is the use of scatter plots and variations of them in 2D and 3D, but also parallel coordinate plots are used, for example [72].

While several visualisation options exist for all LCA goals, certain types of visualisations are only used for one specific LCA goal in the analysed literature, e.g. a pie chart is only used for a part-to-whole comparison to identify hotspots, and a scale is only used to show the result in relation to a benchmark.

4. Discussion

4.1. *Use of visualisations in the design and decision-making process*

4.1.1. *Information requirements*

In contrast to most industrial design products, most buildings are individual designs. Therefore, each design task is approached differently in a different constellation of stakeholders, leading to different required information for decision-making. Nevertheless, tasks within the design process are repeated, and visual information can support when provided in the right way. It is important to define the visualisation strategy considering which are the decisions that should be taken during the design stages.

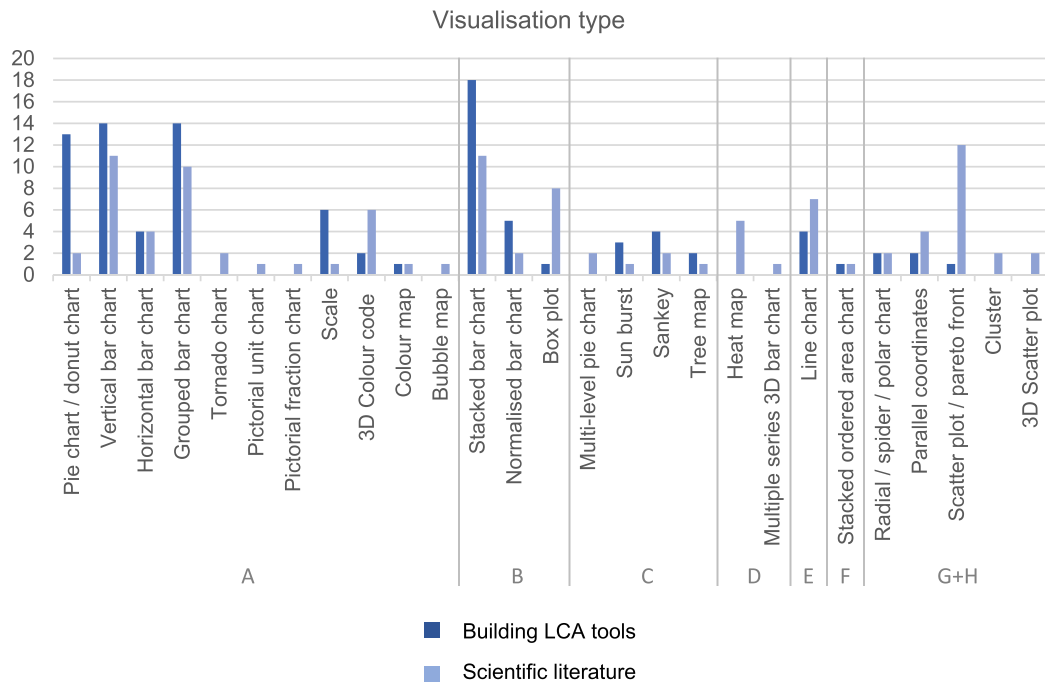


Fig. 4. Number of visualisation types found in the review of building LCA tools and the literature.

Table 2
Number of visualisation types per stakeholder and design phase.

		A											B			C				D		E	F	G+H				
		Pie chart / donut chart	Vertical bar chart	Horizontal bar chart	Grouped bar chart	Tornado chart	Pictorial unit chart	Pictorial fraction chart	Scale	3D Colour code	Colour map	Bubble map	Stacked bar chart	Normalised bar chart	Box plot	Multi-level pie chart	Sun burst	Sankey	Tree map	Heat map	Multiple series 3D bar chart	Line chart	Stacked ordered area chart	Radial / spider / polar chart	Parallel coordinates	Scatter plot / pareto front	Cluster	3D Scatter plot
LCA tools	Decision makers	1	4	0	4	0	0	0	1	0	0	0	5	1	0	0	3	0	0	0	0	0	0	0	2	0	0	0
	Building design prof.	13	13	4	14	0	0	0	6	2	1	0	17	4	1	0	3	4	2	1	0	4	1	2	2	1	0	0
	LCA experts	4	11	0	10	0	0	0	3	1	1	0	9	3	0	0	3	2	0	0	0	3	1	2	2	1	0	0
	Early	5	5	3	6	0	0	0	2	1	0	0	7	2	0	0	1	1	2	0	0	1	0	0	0	0	0	0
	Detailed	9	13	1	10	0	0	0	5	1	1	0	13	4	1	0	3	3	0	1	0	3	1	2	2	1	0	0
Literature	Decision makers	0	3	0	1	0	1	0	0	2	0	0	4	1	3	0	0	0	0	2	0	3	0	0	0	3	1	0
	Building design prof.	2	3	0	7	2	0	1	1	6	0	1	7	0	5	1	1	1	0	0	1	2	0	2	3	8	1	1
	LCA experts	0	7	2	6	0	1	0	0	1	1	1	4	2	2	1	1	2	1	5	0	3	1	2	4	4	1	2
	Early	1	7	3	5	2	0	1	1	5	0	1	4	0	5	1	1	2	0	0	1	1	0	0	4	5	0	1
	Detailed	2	4	1	7	0	1	0	0	1	1	0	8	2	3	1	0	0	1	5	0	7	1	2	0	8	2	1

In terms of LCA, the *overview* part of the information seeking mantra [29] is often related to identifying hot spots on a low level of detail (e.g. operational vs. embodied impact) or the relation to a threshold in a scale to answer the questions whether a national limit value can be met, for example. The overview could also include the comparison of total results of different building variants [84,85].

The *zoom and filter* phase often refers to a hot spot analysis on a more detailed level (e.g. building elements or life cycle phases). This can be implemented using visualisations with a deeper level of hierarchy, such as sun burst diagrams [38] or heat maps [23], amongst others.

The *details on demand* phase can include a very detailed hot spot analysis, e.g. on individual materials or a temporal analysis to identify when impacts are caused. Such information could be confusing in the first interpretation of the LCA results, but very valuable for understanding the background and providing an explanation for results, see [69] for example.

4.1.2. Dynamic visualisations

When implemented in a building LCA tool, in theory, all visualisation options can allow for dynamic and interactive elements. The

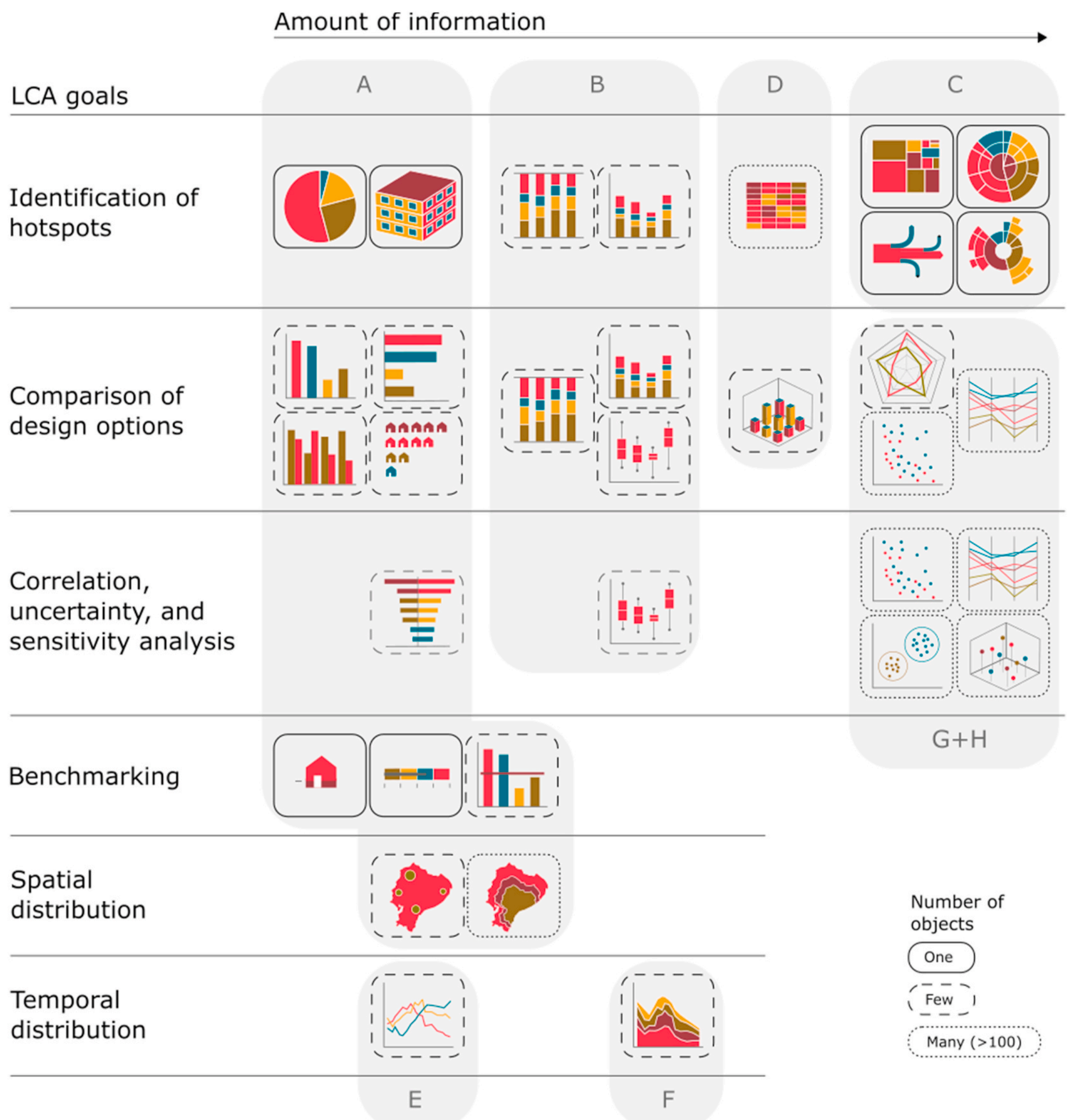


Fig. 5. Synthesis of the LCA goals, the group of visualisation types, and the amount of information displayed in the visualisation.

introduction of interactivity by using dynamic visualisations further enhances the possibilities of how information can be extracted from the charts. We identified three types of possible interactivities. *Subselection or filtering of data* allows to elaborate the further information on one or a set of results and can support the zoom and filter phase. *Expanding deep hierarchy levels* that cannot be displayed at the same time is possible for the visualisation options in group C and can provide the details on demand. Furthermore, *ordering* of the data is possible in different kinds of visualisation, e.g. dynamic bar charts or tornado charts.

4.1.3. *Multi-criteria assessment*

Design and decision processes are complex and usually integrate many criteria. These can be multiple indicators for LCA as shown in group H, but also a combination of LCA results with other performance indicators, such as costs [79] or daylight [86]. The most typical example for visualisation of multiple criteria found in the literature are 2D (or 3D) scatterplots. They show a correlation between two (or three) indicators and allow to identify clusters, trade-offs and Pareto fronts of optima, e.g. Refs. [39,87]. If more than three indicators should be compared spider/radial/polar charts are used, e.g. Ref. [56]. However, they only work for a few objects of assessment and introduce potential bias when interpreting the results [94] (see Table A1 in the Supplementary Information for the advantages and disadvantages). If many design parameters should be visualised at the same time, a common solution consists of parallel coordinates, e.g. Refs. [39,72].

4.2. *From visualisations to design interfaces*

4.2.1. *Dashboards as decision support tools*

An alternative for multi-criteria assessment is a combination of different graphs in dashboards. Dashboards provide the opportunity to visualise different kinds of visualisation types to present information on many criteria at the same time. Furthermore, they allow using different types of visualisations at different levels of details, either for different stakeholders or to follow the information seeking mantra [29]. Adding dynamic visualisations allows for direct interaction and using the visualisations as design tool.

An early example of using a dashboard to visualise LCA results of buildings for decision making is provided by Basbagill et al. [33]. More recently, Houlihan Wiberg et al. [43] and Cho and Houlihan Wiberg [88] developed dashboards for parametric net zero GHG emission neighbourhood (ZEN) developments. The ZEN key performance indicators (KPIs) as defined in the ZEN Definition report [89], such as embodied GHG emissions and transport-related GHG emissions, are visualised amongst other parameters (see Fig. 6). Testing such an interactive tool was carried out on one of the proposed ZEN pilot case studies for a new and retrofit school design in Trondheim, Norway and showed how selected ZEN KPIs and interrelationships between different design parameters can be dynamically visualised to support the decision-making process [88].

4.2.2. Virtual reality to support integrated design processes

Integrated design processes have been proposed to enable the design and implementation of sustainable buildings in practice, supporting communication and the exchange of relevant information amongst the various stakeholders [90]. This is true for all kinds of building projects, but especially important for the development of net zero emission buildings and neighbourhoods. The complexity rises as ever more stakeholders are involved in handling both ‘top down’ neighbourhood level data as well as ‘bottom up’ building and material level information. Considering aspects such as GHG emissions as KPIs is still new and challenging for many policy makers and building design professionals, not to mention citizens, who also need to be included early in participatory, integrated design processes [91]. A more recent approach to support these processes is the use of immersive technologies, such as virtual reality (VR). The potential of using VR to enable users to explore and interact with real design projects was investigated by Houlihan Wiberg et al. [36]. Fig. 7 shows examples of visualisations applied in the virtual environment for presenting information such as a) performance in relation to benchmarks, b) airplane icons as a type of pictorial unit chart, and c) a colour code to visualise the impact of building elements. As such, these visualisation types do not differentiate from the visualisations used on screens or paper. According to Houlihan Wiberg et al. [36], VR offers a more intuitive means to interpret the performance of a building or neighbourhood design and is an invaluable tool to engage users with no prior scientific knowledge. Furthermore, VR provides a means to overcome traditional interdisciplinary barriers by improving communication. These results are in line with Juraschek et al. [92] who emphasize the potential of VR in communicating LCA results and bridging the gap between LCA experts and non-experts.

4.3. Implications and recommendations

The review of the literature emphasised the need for visualisation of LCA results for LCA experts, but especially for stakeholders involved in the design process without detailed LCA knowledge. This need becomes even stronger due to the increased use of LCA results as KPIs in participatory design processes not only on building but also on neighbourhood level.

The analysis of the current building LCA tools showed that most tools

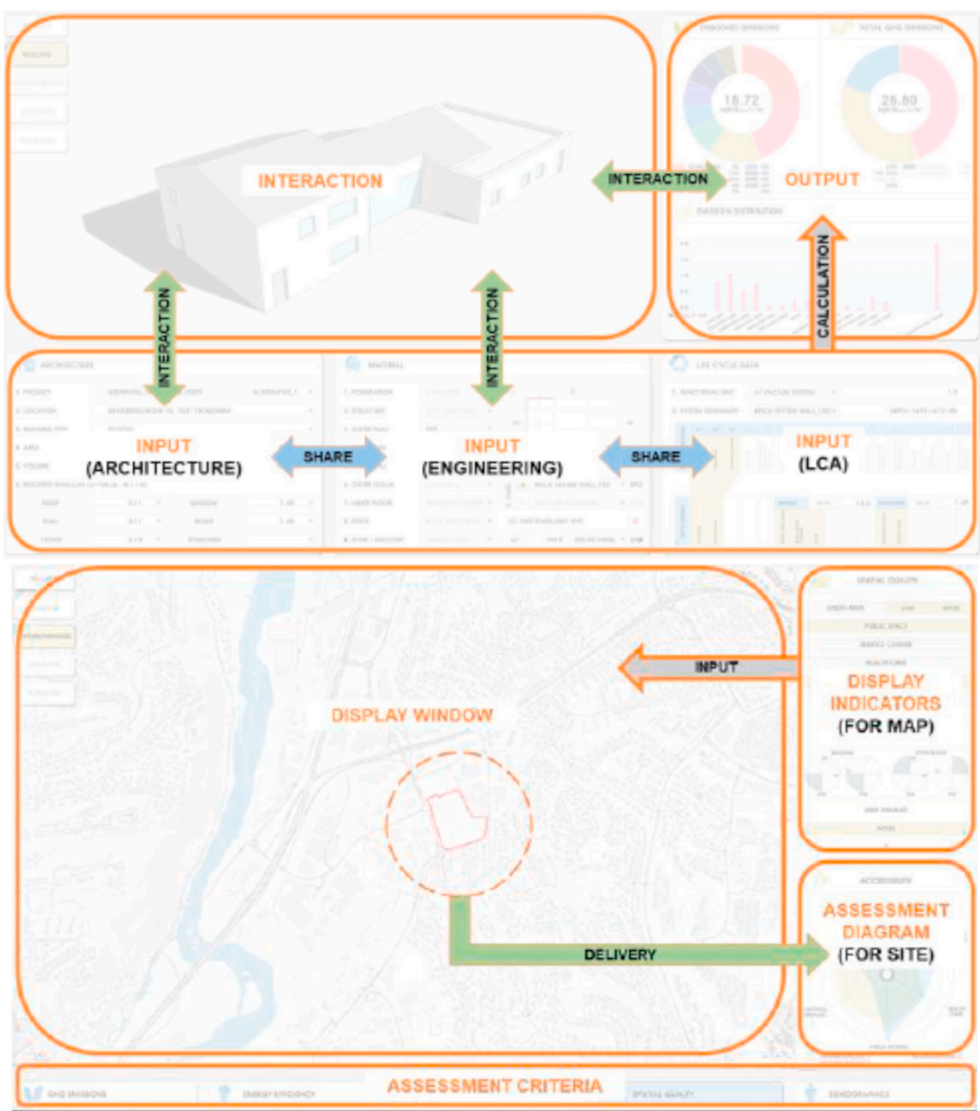


Fig. 6. Dashboard showing the main structure o small zero GHG emissionneighbourhood platform [88].

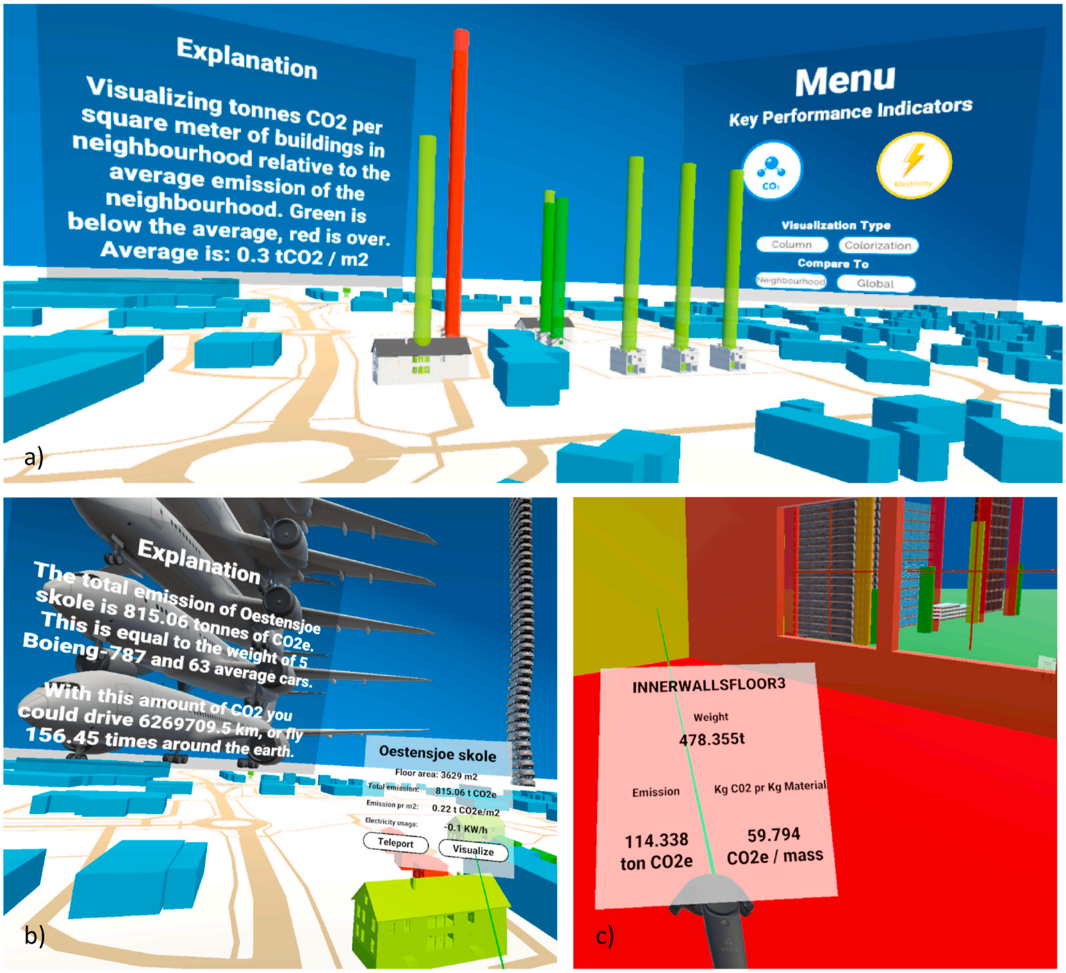


Fig. 7. Snapshots using VR to visualise GHG emissions of buildings [93] using a) red and green columns to show being below or above a treshhold, b) airplane icons to relate GHG emissions of a building to flying, c) a colour code to visualise the impact of building elements. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

use common visualisations such as pie charts or bar charts and variations of them. The review of the literature revealed a variety of more advanced visualisation types. Advanced visualisation types and design interfaces can enable the communication of complex information for LCA experts and building design professionals as well as decision makers concerned with assessing and improving the environmental performance of buildings and neighbourhoods. In general, there is still much room of exploring different visualisation options for presenting LCA-related information and for investigating their suitability for different stakeholder groups. Especially, the use of dynamic visualisations for interactive exploration of the results can support the information seeking during the design process. We would like to propose the synthesis of Fig. 5 as starting point for building LCA tool developers to adapt more visualisation types for different purposes and stakeholders.

In relation to the preferences for different visualisations of stakeholders, the review presented here, is limited. We structured the visualisation types according to the LCA goals, the amount of information shown in the visualisation, and the number of objects. It can be assumed that with the increasing level of LCA knowledge stakeholders have an increasing demand for detailed information. However, this assumption should be verified in studies with stakeholders. We therefore recommend to use the results presented here for stakeholder surveys and interviews in the future. In addition, more case studies and application tests are needed to evaluate the support the visualisations provide in the design process for the final objective of planning more sustainable buildings and neighbourhoods.

5. Conclusions

The need for visualisations has been widely discussed in the literature. The importance of making LCA results understandable for decision makers is growing as LCA is increasingly used in the design process as a basis for environmental performance assessment of buildings and neighbourhoods. This paper presents a review of the most common building LCA tools, which showed that the majority uses common visualisation options, such as pie charts or bar charts. In addition, we systematically reviewed the scientific literature and found a greater variety of visualisations and more complex visualisation options. Most of the complex visualisation with a larger amount of information communicated in the visualisations are used for correlation analysis, multi-criteria optimisation, or uncertainty quantification. Furthermore, a trend towards visualising the results in a 3D design environment is observed.

The discussion highlighted the importance of providing visualisations adapted to the goal and scope of the LCA study, as well as to provide the right amount of information during the design phase to support the information seeking mantra of overview, zoom and filter, and details on demand. Furthermore, we provided examples of how dynamic visualisations can support this process and showed that there is a big potential of combining different visualisations into dashboards which can providean overview and answers to several design questions and LCA goals at the same time. In this paper, we provide a synthesis of LCA visualisation options, which, in combination with the common information seeking mantra, can provide a good starting point for building LCA tool developers and researchers to develop stakeholder-specific dashboards and provide relevant information on the environmental performance of buildings and neighbourhoods. There is a big potential to be adressed in the near future by the LCA and building performance community to make the most of the large variety of visualisation options available.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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